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A Ball-on-Block Impact-Spalling Wear Test and Results on Several Iron Alloys

By R. Blickensderfer and B. L. Forkner

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	lb	pound
cm	centimeter	mg	milligram
diam	diameter	min	minute
ft	foot	OD	outside diameter
HB	Brinell hardness number	pct	percent
hr	hour	vol	volume
ID	inside diameter	wt	weight
in	inch		

A BALL-ON-BLOCK IMPACT-SPALLING WEAR TEST AND RESULTS ON SEVERAL IRON ALLOYS

By R. Blickensderfer[1] and B. L. Forkner[2]

ABSTRACT

An impact wear testing machine was devised by the Bureau of Mines that simulates the repeated impact conditions encountered in large milling and grinding operations where breakage and spalling are problems. The apparatus provides data on materials that may help in the design of alloys with improved resistance to deformation, spalling, and breakage. The test blocks are 2 in thick by 6 in by 8 in. Impacts are produced by dropping 3-in-diam balls weighing 4 lb from a height of 10 ft. Tests were run until breakage occurred or to a total of 100,000 impacts. Four types of failures of the test block were observed: (1) cold flow of the bulk material by plastic deformation, (2) flaking of the surface in the impact region, (3) spalling of the block to form a crater in the region of impact, and (4) breakage of the test block into two or more major pieces. The effects of composition, heat treatment, microstructure, and hardness on types of failure are discussed.

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INTRODUCTION

Many tons of metals are lost annually by wear of equipment used for mining and processing minerals. The Bureau of Mines is conducting research on causes of wear and ways to reduce wear losses, especially of strategic and critical metals such as chromium, manganese, and cobalt.

The abrasive wear that occurs during crushing and grinding has prompted the development of alloys with greater wear resistance. Manganese steel was one of the earliest wear-resistant alloys, developed 100 years ago, and is still used widely. The ability to work harden that provides manganese steel with its abrasion resistance can result in cold flow with significant dimensional changes. Mill liners of manganese steel expand as a result of the cold flow caused by repeated impacts during milling. The expansion may rupture the mill shell, and the cold flow of the liners around the bolts and around each other makes the liners almost impossible to remove for replacement. Manganese steel is widely used to line the outer surface of cones in gyratory crushers and to line the faces of jaw crushers but not to line rod mills or ballmills. More flow-resistant materials, namely, hardenable steels or cast irons, are used to line rod mills and ballmills.

For over 50 years, alloyed white cast irons have been recognized for their high resistance to abrasive wear. However, the brittleness of white irons, especially the early nickel white irons, limited them to applications of low impact. There is considerable information in the literature about the abrasive wear resistance of many different alloys in general (2-3, 5, 10, 16, 19)[3] and white cast iron in particular (7, 9, 11-12, 15, 17-18), to cite a few. In recent decades, the impact resistance and the abrasive wear resistance of Ni-Cr and Cr-Mo white irons have been improved. The alloyed white irons are now used widely for liners in rod mills and ballmills.

As new mills were made in larger diameters and rods and balls were made larger, impact forces become more severe on mill liner materials. In addition to breakage, the alloyed white irons have a propensity to spall when subjected to repeated impacts. One spall may represent a greater loss of material than many hours' worth of abrasive wear.

Improvements in mill liner materials have evolved slowly owing to the time required for interactions to take place between foundrymen, heat treaters, and mill operators. Much testing and many metallurgical studies of mill liner materials have been made, but there is still a need for systematic metallurgical studies based on a rapid test that simulates milling conditions to determine the mechanisms of wear.

Improved methods for evaluating mill liner materials are needed to improve the mechanical properties of the present types of alloys and to study new alloys, particularly those that contain lesser amounts of strategic materials.

It has been quite difficult to produce cold flow, spalling, and breakage on large-scale specimens under controlled laboratory conditions. Large-scale, repeated impact tests were developed by Dixon (9), Durman (13), and Blickensderfer and Tylczak (4). The testing machines used balls to produce the impacts. The balls were lifted 11 to 21 ft and allowed to fall. In the first two machines, the balls struck a massive anvil and rebounded to a second anvil. Considerable information on the number of impacts required to fracture various alloys was obtained on balls and anvils, but no spalling was reported. In the third machine, a ball dropped onto a line of balls, which produced a series of impacts down the line. The test had the advantages of producing many impacts per ball drop and providing very severe impacts on

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

the first few balls in the line. Spalling was produced in this machine on balls of certain alloys, especially the alloyed white irons.

Impact tests, such as the Izod and Charpy, are of essentially no value for predicting the spalling and fracture resistance of mill liners. The standard impact specimens are relatively small and subject to only one impact; however, mill liners are large and receive large numbers of impacts that can develop large compressive stresses near the surface. Even fracture toughness tests are of little value for predicting spalling and fracture behavior of alloyed white cast irons (1, 8).

In the present test, an anvil is the test block upon which hardened steel balls are dropped to produce impacts. The rectangular test block more closely resembles a mill liner or crusher casting than does the ball test specimen of the other balldrop tests.

EXPERIMENTAL PROCEDURE

BALL-ON-BLOCK IMPACT WEAR MACHINE[4]

The test apparatus provides a means for dropping 4-lb steel balls 10 ft onto a test block. The machine, as shown in figures 1 and 2, consists of a lightweight steel frame, a conveyor and ramp system for transporting the balls, and an anvil for supporting a test block inside a large funnel that collects the rebounding balls. The angle-iron frame is 14 ft high and 4-1/2 ft square. A rubber belt conveyor with nylon buckets lifts the balls to the top. The upper belt conveyor is driven by a gear-head motor and a chain reduction drive mounted on top of the frame. The conveyor travels at 126 ft/min. Mounted on the top of the frame is a ball-catching ramp to direct the balls to the vertical drop tube. The drop tube, 3-1/4 in ID by 7-1/2 ft long, guides the balls to the test block. The lower end of the tube is 2-1/2 ft above the test block to allow space for rebounding balls.

The bottom frame support is rather massively constructed of I-beam steel. A subframe supports a rubber-lined steel tub, with a cone-shaped lower section, for collecting the bouncing balls. It has an 8-in-diam opening at the bottom. Under the opening, an inclined ramp catches the balls and returns them to the conveyor pickup point.

In the center of the collecting tub a heavy steel base plate and hold-down fixtures hold the test block in place (fig. 3). The sample block is tilted about 5° in order that a rebounding ball is less likely to strike the next ball.

The balls used were nominally 3-in-diam commercial grinding balls made of high-carbon, low-alloy steel, and heat treated by the supplier to a Brinell hardness greater than HB 650.

Mounted on the frame is a sand hopper with a hose that carries sand to a side port located 8 in from the lower end of the drop tube. The sand trickles onto the test block in the region of ball impact. The sand eventually finds its way to the bottom of the conical tub, through small holes in the ball ramp, and into a collecting box. The sand is used to more closely approach the impact conditions in a real ballmill in which ore is usually present at the point of impact between a ball and liner.

An interruptible light-beam counter on the lower ramp monitors the number of balls that pass.

OPERATION

Before starting up the machine, a test block is fastened in the holder. The protective screens around the top of

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[4]The authors wish to acknowledge Jeffrey S. Hansen, metallurgist, Albany Research Center, for the initial engineering design of the equipment that subsequently led to the present machine.

FIGURE 1. - Ball-on-block impact wear testing machine.

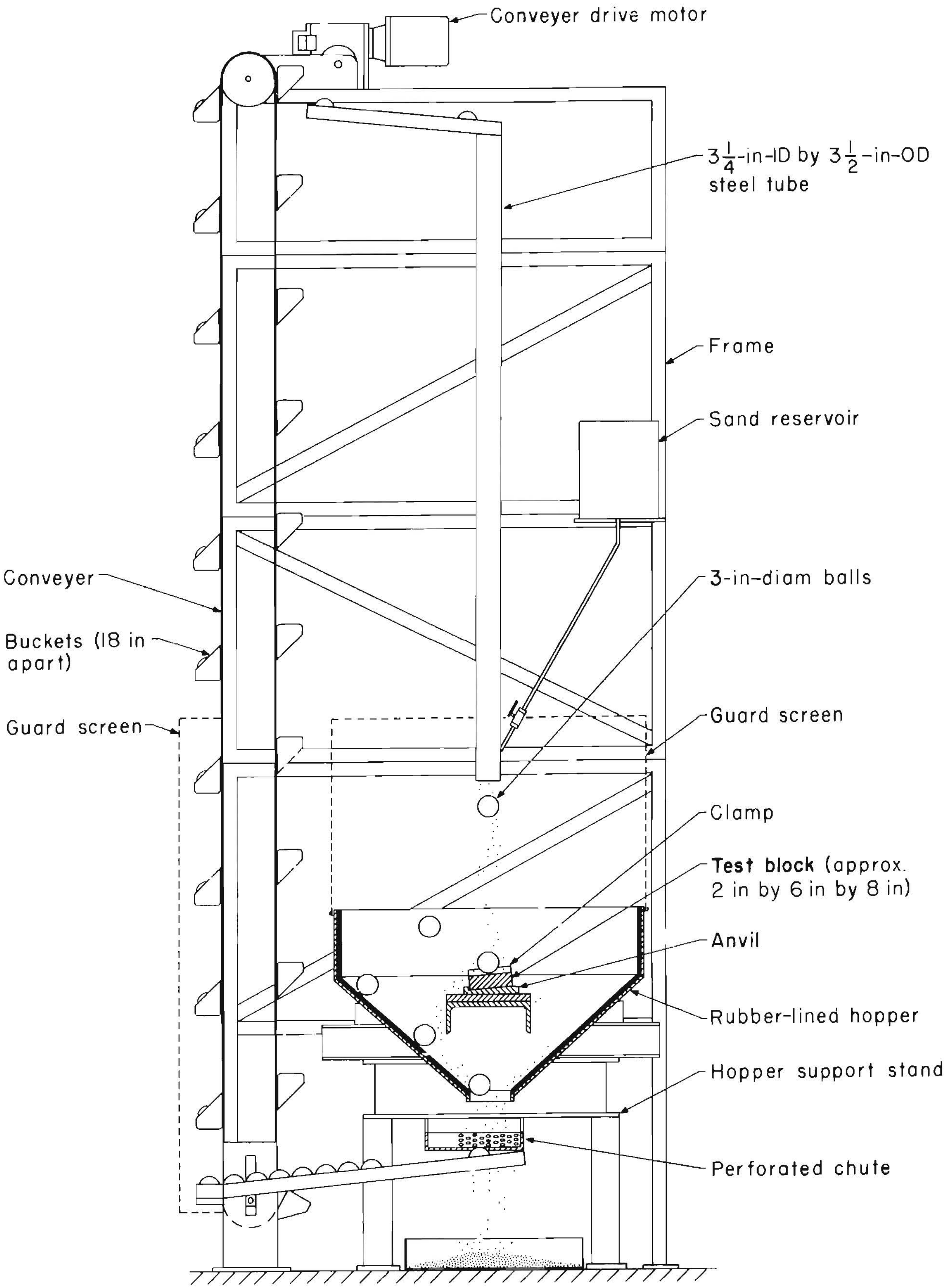

FIGURE 2. - Schematic of the ball-on-block testing machine.

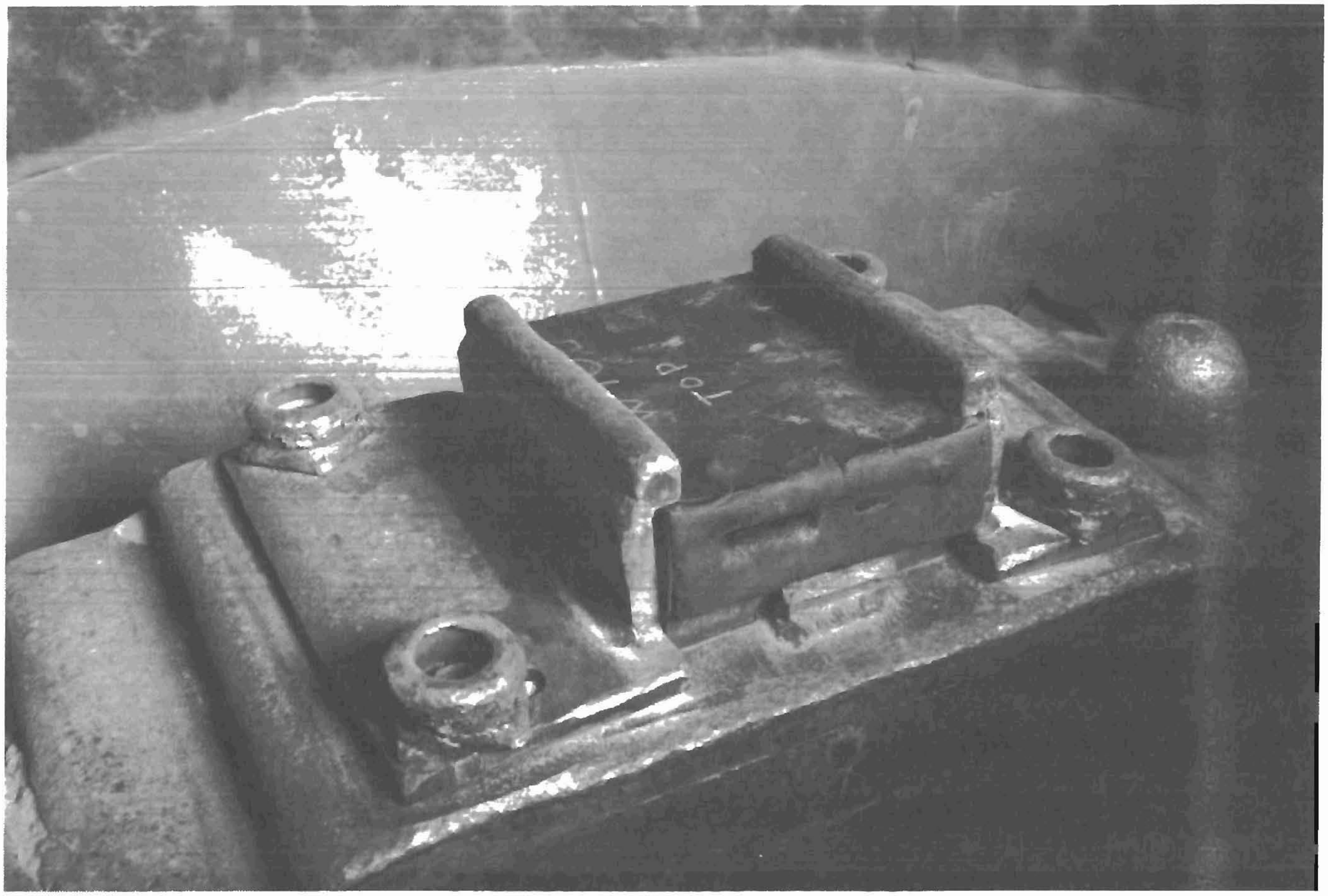

FIGURE 3. - Test block mounted in testing machine.

the ball collecting tub are installed. Twelve balls from a known lot are put into the bottom ramp. To start up the machine, the conveyor is turned on, and the sand flow is turned on and adjusted to 6 to 8 lb/hr. Considerable bouncing of the balls from the test block and the rubber-lined tub occurs before they find their way out the bottom opening. Impacts on the test block occur at a rate of about 2,000 per hour not including occasional light impacts from rebounding balls.

TEST BLOCKS

The alloy compositions selected for evaluation of the test equipment represent a wide range of typical wear-resistant alloys used in mining and milling applications. The alloys selected were expected to provide differences in modes of failure during the test. Alloys included mild steel, austenitic-manganese steel, high-carbon steel, low-alloy steels, lean-manganese alloy steel, pearlitic-cast iron, and a variety of alloyed white cast irons. The alloys, including their chemical analysis, are listed in table 1. Except for three commercial castings, the test blocks were prepared in the laboratory. Alloys were melted in a 100-lb air induction furnace and poured into a graphite mold. The shrink cavity was minimized by adding an exothermic compound onto the top.

Test blocks were 6 in wide, approximately 8 in long, and 2 in thick. The 6- by 8-in face was the impact surface. Before testing, the blocks were sandblasted and heat treated. The heat treatments (table 1), included a wide range of cooling rates and tempering temperatures. Solution treatments or re-austenitizing treatments that were done at temperatures of 1,000° C or higher

TABLE 1. - Composition and heat treatment of test blocks

Block	Alloy	Analysis, wt-pct									Heat treatment[1]
		C	Si	Mn	Cr	Mo	Ni	Cu	P	S	
1.....	Mild steel, AISI 1020	0.18	ND	0.44	ND	ND	ND	ND	ND	0.039	Hot-rolled condition.
2.....	Austenitic Mn steel..	1.24	0.44	12	0.23	ND	0.10	ND	ND	ND	1,400° C for 2 hr, WQ.
3.....	High-carbon Cr steel.	1.45	1.05	.39	1.44	0.04	.10	ND	0.02	.018	1,040° C for 2 hr, AC; 840° C, OQ; temper at 260° C.
4.....	Lean Mn, Cr-Mo steel.	1.29	.45	6.44	.82	1.01	.26	ND	.08	ND	1.040° C for 2 hr, FC.
5.....	Pearlitic Cr-Mo steel	.91	.61	.74	2.51	.45	.27	ND	ND	.024	1,040° C for 6 hr, OQ; temper at 290° C.
6.....	Martensitic Cr-Mo steel.	.95	.58	1.57	2.3	.41	.62	0.11	.043	.014	1,010° C for 2 hr, AC.
7.....	Pearlitic cast iron..	3.13	.44	1.7	.21	ND	.18	.23Al	ND	ND	1,040° C for 2 hr, WQ.
8.....	Martensitic-graphitic iron.	3.20	1.16	1.16	.58	ND	ND	ND	.035	.008	870° C for 3 hr, OQ; temper at 315° C.
9.....	Ni white cast iron...	3.16	.25	.56	1.56	.04	3.7	ND	.01	.028	450° C for 4 hr, AC; 275° C for 4 hr, AC.
10.....	Ni-Cr white cast iron	2.81	1.35	1.29	9.40	ND	5.37	ND	ND	.012	775° C for 12 hr, slow FC (20 hr).
11.....	.....do..............	3.85	1.10	2.1	9.42	.66	5.31	ND	.02	.023	775° C for 6 hr, AC; temper at 220° C.
12a,b,c	High Cr-Mo white cast iron.	2.82	.32	1.0	20.8	1.1	.64	.19	ND	.043	Unknown, commercial.
13.....	.....do..............	2.64	.22	.48	17.9	1.1	.49	ND	.03	.067	1,010° C for 4 hr, AC; temper at 510° C 12 hr, AC.
14.....	.....do..............	2.83	.51	1.2	18.1	2.3	1.1	2.3	.055	.063	1,000° C for 8 hr, fan cool to 540° C, AC.

ND Not determined.
[1]AC Air cool. FC Furnace cool. OQ Oil quench. WQ Water quench.

were conducted in cast iron chips to prevent decarburization.

After heat treatment, the blocks were visually inspected for cracks and other defects; if none were found, the blocks were weighed, measured, and the Brinell hardness was determined. The back (bottom) of the block was ground flat to give good contact with the anvil.

A complete test for a block normally entailed a total of 100,000 impacts. After 10,000, 20,000, 35,000, and 60,000 impacts, the block was removed from the holder and inspected for cracks, spalling, and other impact damage. Any damage was noted and recorded. The block was weighed and the size of the crater was measured. The block was then reinstalled for further testing. If the block fractured, the test was terminated and the pieces were collected, weighed, and inspected. The volume of the crater was measured if possible. If a failure was associated with a preexisting crack or casting flaw, the test was disqualified and was not included in this report.

Although each liner in a real ballmill could be expected to receive millions of ball impacts during its lifetime, it is believed that 100,000 impacts concentrated in one spot, as in the present test, represents a severe test with the advantage that it can be completed in a test time of 50 hr or less.

After the ball-on-block tests were completed, test specimens for metallography and abrasive-wear tests were cut from the blocks with a slow-speed band saw using a tungsten-carbide-tipped blade. The microstructures of the test blocks are given in table 2. The abrasive wear tests have not been completed at this time.

TABLE 2. - Microstructure of test blocks

Block	Alloy	Microstructure
1.....	Mild steel................	Ferrite and pearlite.
2.....	Austenitic Mn steel.......	Austenite, equiaxed grains with numerous small precipitates.
3.....	High-carbon Cr steel......	About 2 pct interdendritic eutectic carbides and traces of graphite in bainite.
4.....	Lean Mn, Cr-Mo steel......	About 40 pct pearlite in continuous austenite.
5.....	Pearlitic Cr-Mo steel.....	Tempered martensite.
6.....	Martensitic Cr-Mo steel...	Masses of coarse martensite in prior dendritic austenite.
7.....	Pearlitic cast iron.......	Primarily pearlite; intergranular carbides.
8.....	Martensitic-graphitic iron	Type A graphite flakes and 5 pct interdendritic carbide in martensite matrix.
9.....	Ni white cast iron........	Very coarse interdendritic eutectic of Fe-Cr carbides; dendritic coarse martensite.
10.....	Ni-Cr white cast iron.....	Interdendritic acicular Fe-Cr carbides; dendrites of tempered martensite.
11.....	.....do...................	Very fine-grained network of Fe-Cr carbides in austenite with traces of martensite.
12a,b,c	High Cr-Mo white cast iron	Interdendritic acicular Fe-Cr carbides; continuous austenite with secondary carbides and some martensite.
13.....	.....do...................	Continuous interdendritic Fe-Cr carbides; dendrites of tempered martensite.
14.....	.....do...................	Relatively coarse interdendritic Fe-Cr carbides; dendritic austenite with secondary carbide precipitates.

RESULTS AND DISCUSSION

The failures that occurred in the test blocks after repeated impacts by 3-in balls were classified into four types: cold flow, flaking, spalling, and breakage. Cold flow describes the bulk displacement of metal by plastic deformation. Flaking refers to the formation and separation of very thin pieces of metal caused by repeated plastic deformation in the region of impact. Spalling describes the separation of relatively large pieces of metal, about 1/8 to 1/4 in across, from the surface in the region of repeated impact. Breakage means that the block fractured into two or more major pieces. The test results are given in table 3.

Cold flow occurred in four test blocks, primarily the softest ones. Flaking occurred in these same four blocks and in two additional ones. Spalling occurred in six test blocks, all of which were alloyed white cast irons; furthermore, four of these broke before reaching 100,000 impacts. Five additional blocks broke, one of which exhibited flaking before breaking. The weight loss of blocks ranged from 0.09 mg per impact for minimum flaking to 5.1 mg per impact for maximum spalling. The rates at which blocks lost weight are shown by the slopes of the curves in figure 4. The rates of weight loss decreased for several alloys as the test progressed. For example, the high Cr-Mo white cast iron, (block 13), lost weight very slowly beyond 20,000 impacts.

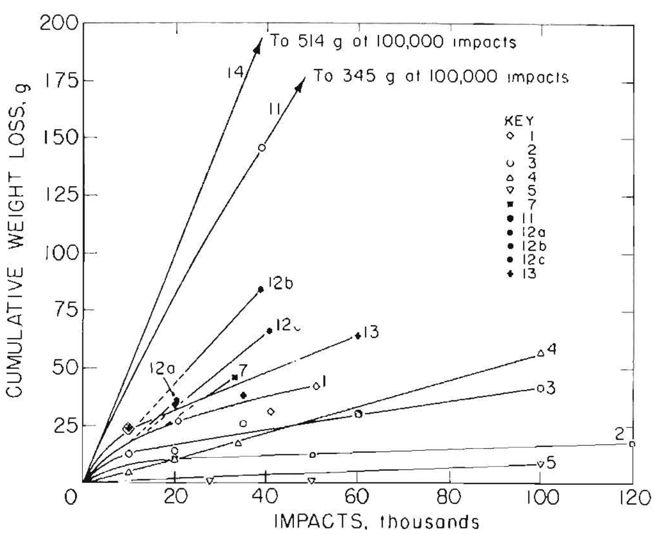

FIGURE 4. - Wear rates of test blocks.

In real ballmills, only three of these types of failures have been reported; namely, cold flow, spalling, and breakage. Flaking is not observed in real mill liners apparently because the abrasive wear rate is faster than the flaking rate; therefore, the surface layers are removed before flakes can form.

COLD FLOW

Cold flow is closely related to flaking, described in the next section, because both result from plastic deformation. The greatest amount of cold flow was observed in the two softest alloys, as might be expected; namely, blocks 1 and 2, mild steel and austenitic-manganese steel. As shown in figures 5 and 6, the impact region deformed by developing a broad crater and by flowing outward to form a lip of flowed metal on the end of the block. The volume of the impact crater in the mild steel was approximately 1 in^3 for 50,000 impacts; for the manganese steel it was 2 in^3 for 120,000 impacts, nearly the same cold flow volume per impact (table 3). Blocks 3 (high-carbon chromium steel) and 4 (lean-manganese steel) were the only others to cold flow to a measurable degree. Block 3 developed a crater of 0.43 in^3 and block 4 a crater of 0.17 in^3 after 100,000 impacts each, a cold flow rate of only 1.7×10^{-6} in^3 per impact or about 10 pct of that of the first two blocks.

Although the extent of cold flow cannot be accurately measured by this ball-on-block test, the results on mild steel and

TABLE 3. - Summary of test results

Block	Type of alloy	Brinell hardness (HB)	Number of impacts	Weight loss per impact, mg	Type of failure	Diameter, in	Depth, in	Volume, in^3	Volume per impact, 10^{-6} in^3
1...	Mild steel................	156	50,000	0.82	Cold flow, flaking	5.0	0.1	0.98	19.6
2...	Austenitic Mn steel.......	[1]227	120,000	.15	.....do...........	4.5	.25	2.00	16.7
3...	High-carbon Cr steel......	415	100,000	.42	.....do...........	2.4	.19	.43	4.3
4...	Lean Mn, Cr-Mo steel......	555	100,000	.57	.....do...........	1.8	.13	.17	1.7
5...	Pearlitic Cr-Mo steel.....	550	100,000	.09	Flaking...........	2.3	.11	.17	1.7
6...	Martensitic Cr-Mo steel...	600	1,900	([2])	Breakage..........		None		
7...	Pearlitic cast iron.......	440	33,400	1.4	Flaking, breakage.	2.0	.16	.25	7.5
8...	Martensitic-graphitic iron	514	130	([2])	Breakage..........		None		
9...	Ni white cast iron........	580	13,600	([2])	.....do...........		Negligible		
10...	Ni-Cr white cast iron.....	612	3,300	([2])	.....do...........		None		
11...	.....do..................	585	100,000	3.5	Spalling..........	3.8	.43	1.7	17.0
12a..	High Cr-Mo white cast iron	555	20,600	1.7	Spalling, breakage		Negligible		
12b..	.....do..................	555	38,800	2.2	.....do...........	1.0	.10	.04	1.0
12c..	.....do..................	555	40,300	1.6	.....do...........		Negligible		
13...	.....do..................	668	77,600	1.1	.....do...........	1.3	.10	.07	.9
14...	.....do..................	670	100,000	5.1	Spalling..........	4.2	.44	3.36	33.6

[1]HB 555 at end of test, by work hardening.
[2]Loss of broken fragments prevented determination of weight loss.

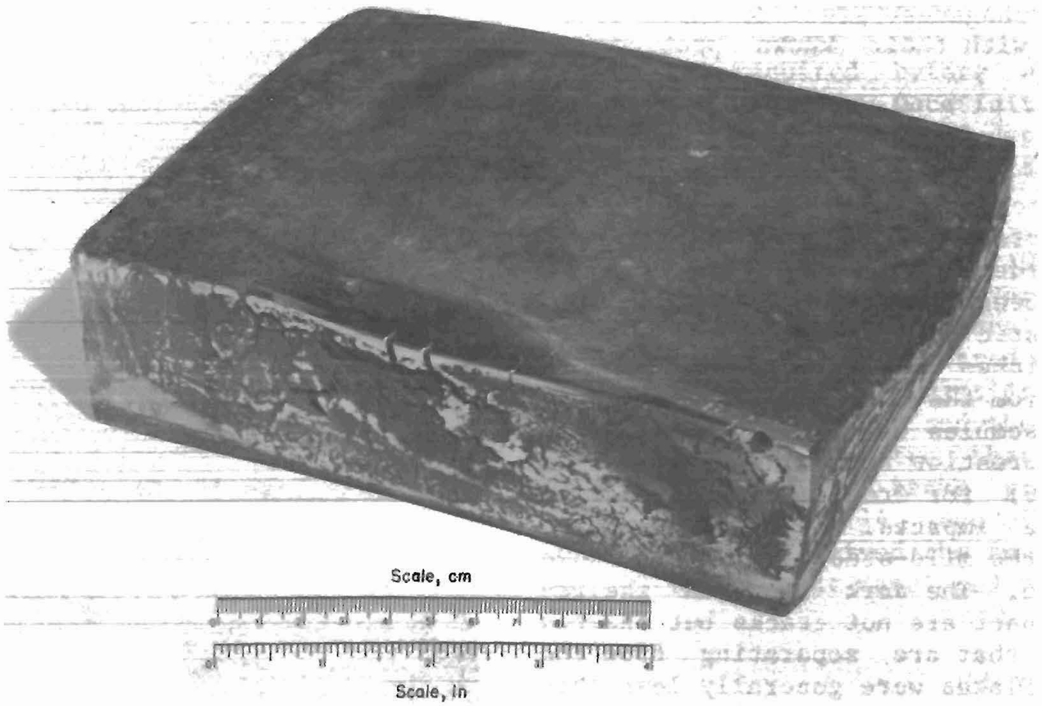

FIGURE 5. - Cold flow of a test block. Austenitic Mn steel (block 2) after 120,000 impacts.

FIGURE 6. - Flaking of a test block. Mild steel (block 1) after 50,000 impacts.

austenitic-manganese steel do agree qualitatively with their known problems of cold flow.

FLAKING

Flaking occurred after repeated impacts on the surface of the test blocks that were no harder than HB 555 and did not spall or break. As the result of repeated plastic deformation of the surface regions, flakes formed and eventually separated from the surface. This flaking closely resembles the threshold mechanism of flake formation reported by Brown and Edington (6) for erosion caused by solid-particle impacts. Partially formed flakes in the mild-steel block are shown in figure 6. The dark lines in the region of impact are not cracks but shadows of flakes that are separating from the surface. Flakes were generally less than 0.1 in across and very thin. Examination of the flakes by electron microscopy revealed that the edges could be penetrated by electrons, which indicated a thickness on the order of 10^{-6} in.

Photomicrographs of a flake of mild steel (block 1) that separated after 20,000 impacts are shown in figure 7. At X 50 the distraught nature of the surface with a tangled fine structure is seen. At X 500, the surface of the flake appears uneven and contains small particles. At X 2,500, the surface appears relatively rough and is definitely covered with numerous small particles. From a silicon analytical scan, the light-colored particles were deduced to be fragments of silica sand.

The alloys that flaked were generally the softer ones, and all were steels except the pearlitic cast iron, which had the highest flaking rate of all. The alloys that flaked, in order of decreasing rate of weight loss, were pearlitic cast iron, mild steel, lean Mn Cr-Mo steel, high-carbon chromium steel, austenitic-manganese steel, and pearlitic Cr-Mo steel. The pearlitic cast iron was the only specimen in this group that broke (33,400 impacts) before reaching the full normal test of 100,000 impacts.

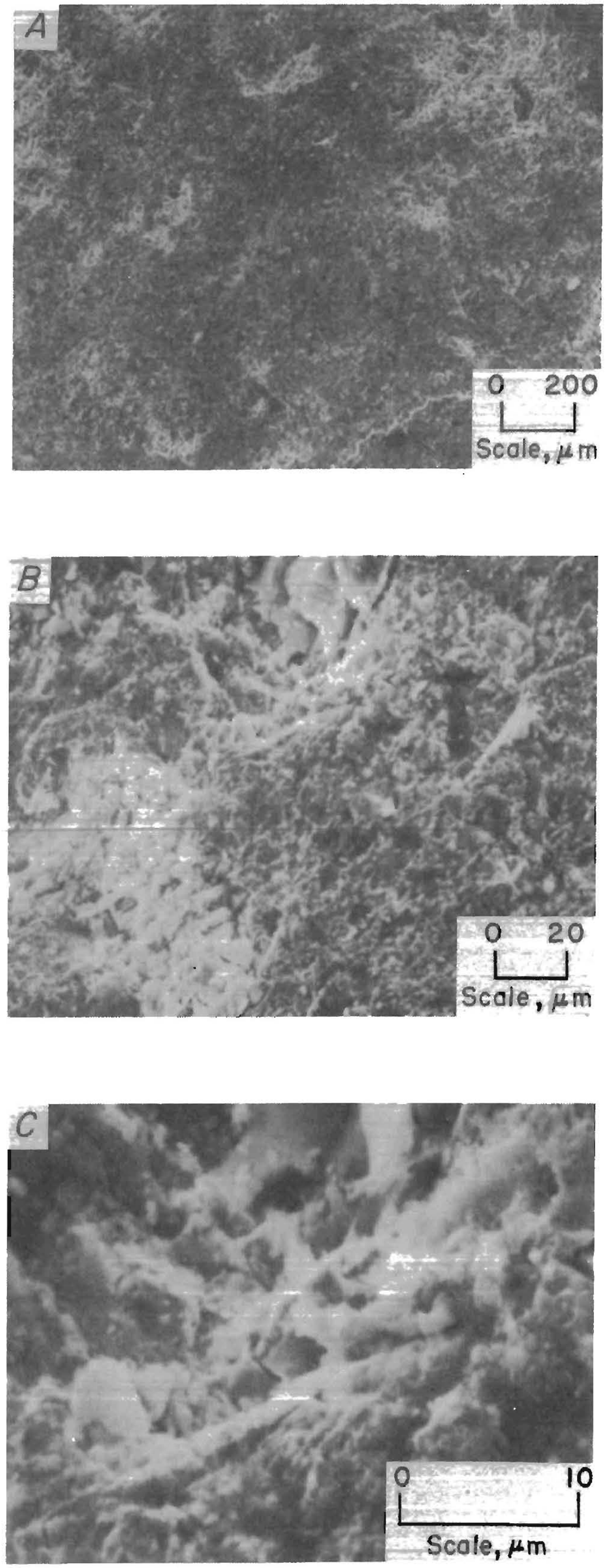

FIGURE 7. - Flake debris. Mild steel (block 1). *A*, X 50; *B*, X 500; *C*, X 2,500.

The weight losses caused by flaking were almost negligible. Based on total losses and total number of impacts, the losses ranged from 0.09 mg per impact for block 5 (pearlitic Cr-Mo steel) to 1.4 mg per impact for block 7 (pearlitic cast iron). The latter value is actually high because in block 7, the only one in this group to break, a significant amount of edge chipping occurred around the fracture; therefore, the weight loss was not totally due to flaking. Discounting block 7, the values for flaking loss ranged from 0.09 mg per impact for block 5, to 0.82 mg per impact for block 1, the softest and most ductile block.

SPALLING

Most of the alloyed white cast irons, known to be very hard and abrasion resistant, lost material by spalling. Normally, at least 5,000 to 10,000 impacts were required before a spalling crater was observed. Once initiated, the crater grew in diameter and depth as impacting continued. Figure 8 shows a large crater 3 to 4 in across by 0.43 in deep that developed in test block 11 (Ni-Cr white cast iron) after 100,000 impacts. The crater was over 2 in. in diameter after 40,000 impacts. As seen in table 3, spalling occurred on six of the eight alloyed white cast iron blocks; namely, the Ni-Cr block and the five high Cr-Mo blocks. The two that did not spall, 9 and 10, broke prematurely. Block 11 and block 14, one of the high Cr-Ni blocks, survived the full test of 100,000 impacts but developed the largest crater.

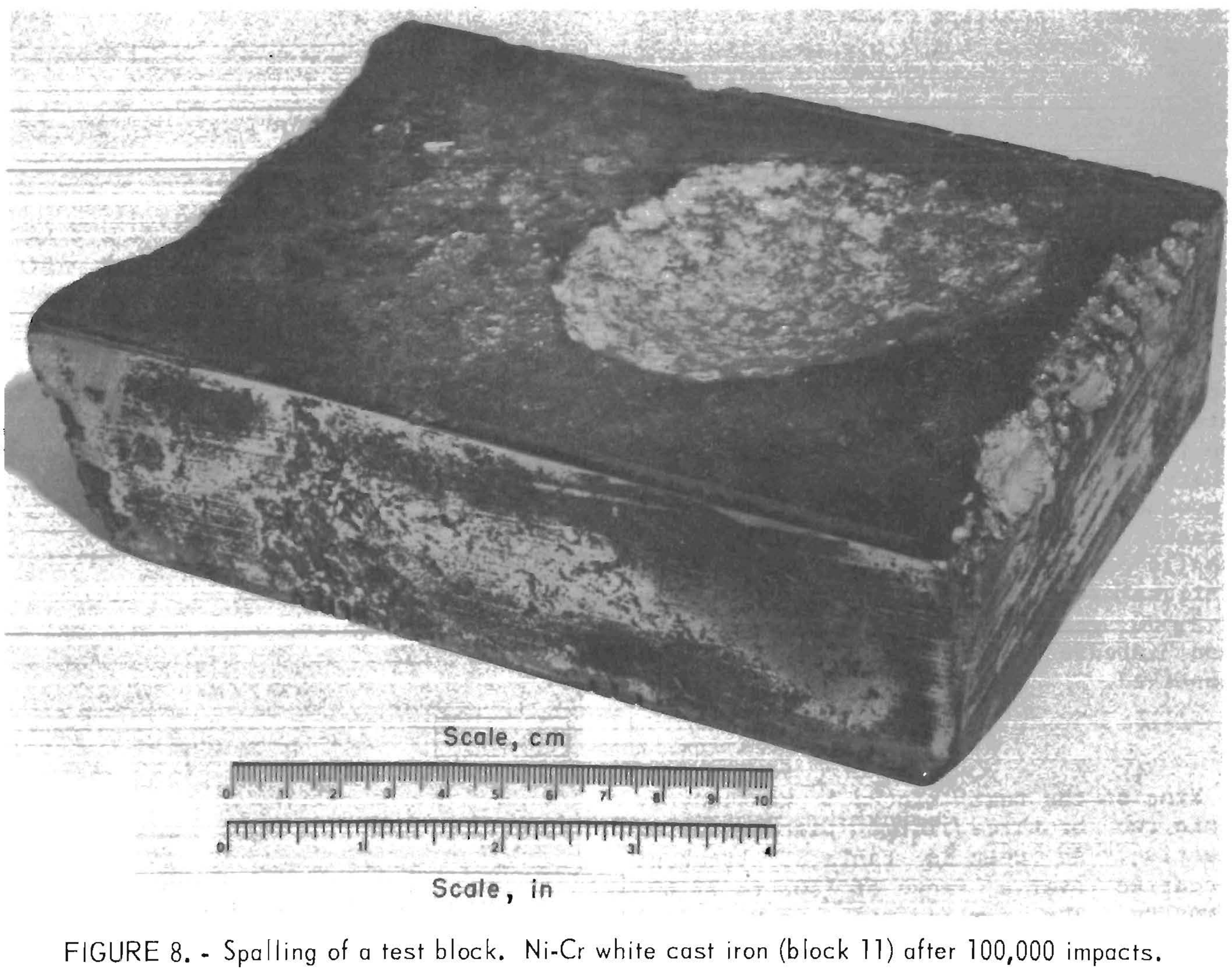

FIGURE 8. - Spalling of a test block. Ni-Cr white cast iron (block 11) after 100,000 impacts.

The size of the crater, relative to the number of impacts, gives an indication of the tendency to spall. The weight loss per impact is not as good an indicator of spalling because it includes edge chipping that is not necessarily related to the spalling tendency. The spalling rates are better defined in terms of volume of impact crater formed per impact. The rates are included in table 3.

The triplicate high Cr-Mo blocks, 12a, 12b, and 12c, resisted spalling well until they broke at 20,600 to 40,300 impacts, when only small craters had developed. The other two high Cr-Mo blocks, 13 and 14, spalled at extremely different rates. Block 13 developed only a small spalling crater until it broke at 77,600 impacts, for a rate of 0.9×10^{-6} in^3 per impact; block 14 developed the largest spalling crater of any block and had the highest spalling rate, 33.6×10^{-6} in^3 per impact. Both blocks were reaustenitized at about 1,000° C, but block 13 was tempered for 12 hr at 510° C, whereas block 14 was not tempered. Thus, the tempering treatment apparently reduces spalling but increases the tendency to break. The optimization of spalling resistance, breakage resistance, and abrasive wear resistance is being studied further.

Photomicrographs of a piece that spalled from block 14 are shown in figure 9. At X 50, the surface is seen to be interrupted by a number of cracks. Coarse and very fine silica particles are imbedded in the surface. At X 500, finer cracks are seen that surround imminent spalls of much smaller size. A hint of fatigue striations is also seen. At X 2,500, greater details of the platelets and imbedded silica particles can be observed.

BREAKAGE

Nine of the test blocks broke suddenly into two or three large pieces during testing. As seen in table 3, breakage occurred over a range of 130 to 77,600 impacts. The martensitic Cr-Mo steel (block 6) broke at 1,900 impacts; the

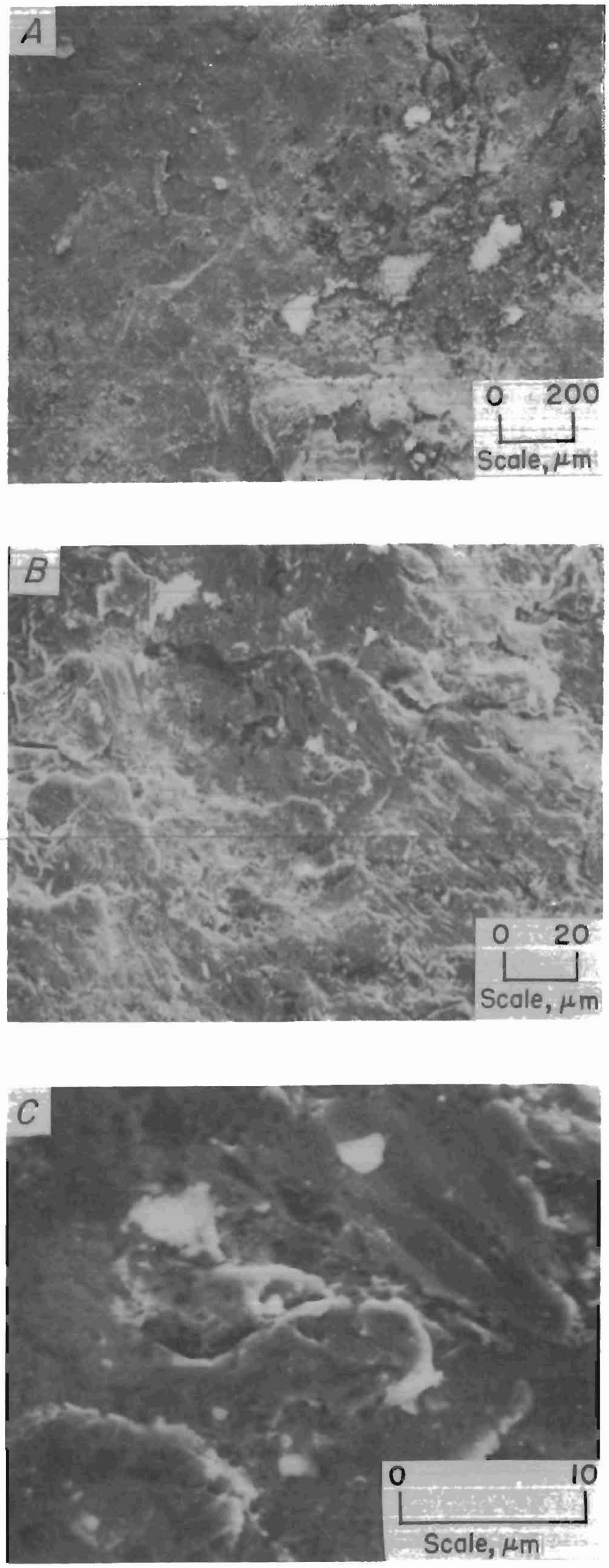

FIGURE 9. - Spall debris. High Cr-Mo white cast iron (block 14). *A*, X 50; *B*, X 500; *C*, X 2,500.

pearlitic cast iron (block 7) broke at 33,400 impacts after developing a small flaking crater. The martensitic-graphitic cast iron (block 8) had the shortest life of any block--130 impacts. The Ni (block 9) and Ni-Cr white cast irons (block 10) survived 13,600 and 3,300 impacts, respectively. The other Ni-Cr white cast iron (block 11) did not break.

The three high Cr-Mo white iron blocks (12a, 12b, and 12c) developed small spalling craters before they broke. Figure 10 shows block 12c after failure at 40,300 impacts. Part of the spalling crater can be seen in the figure. However, most of the crater was destroyed by chipping and fracturing that occurred after the block broke but before the ball dropping was stopped, which was typical for most of the blocks that broke. Block 13 almost survived the test but broke at 77,600 impacts.

An indication of the reproducibility of the test can be learned from specimens 12a, b, and c. These three similar blocks failed between 20,600 and 40,300 impacts, and the weight loss was fairly consistent between 1.6 and 2.2 mg per impact. An indication of the validity of the test is given by block 8 (martensitic-graphitic cast iron) which

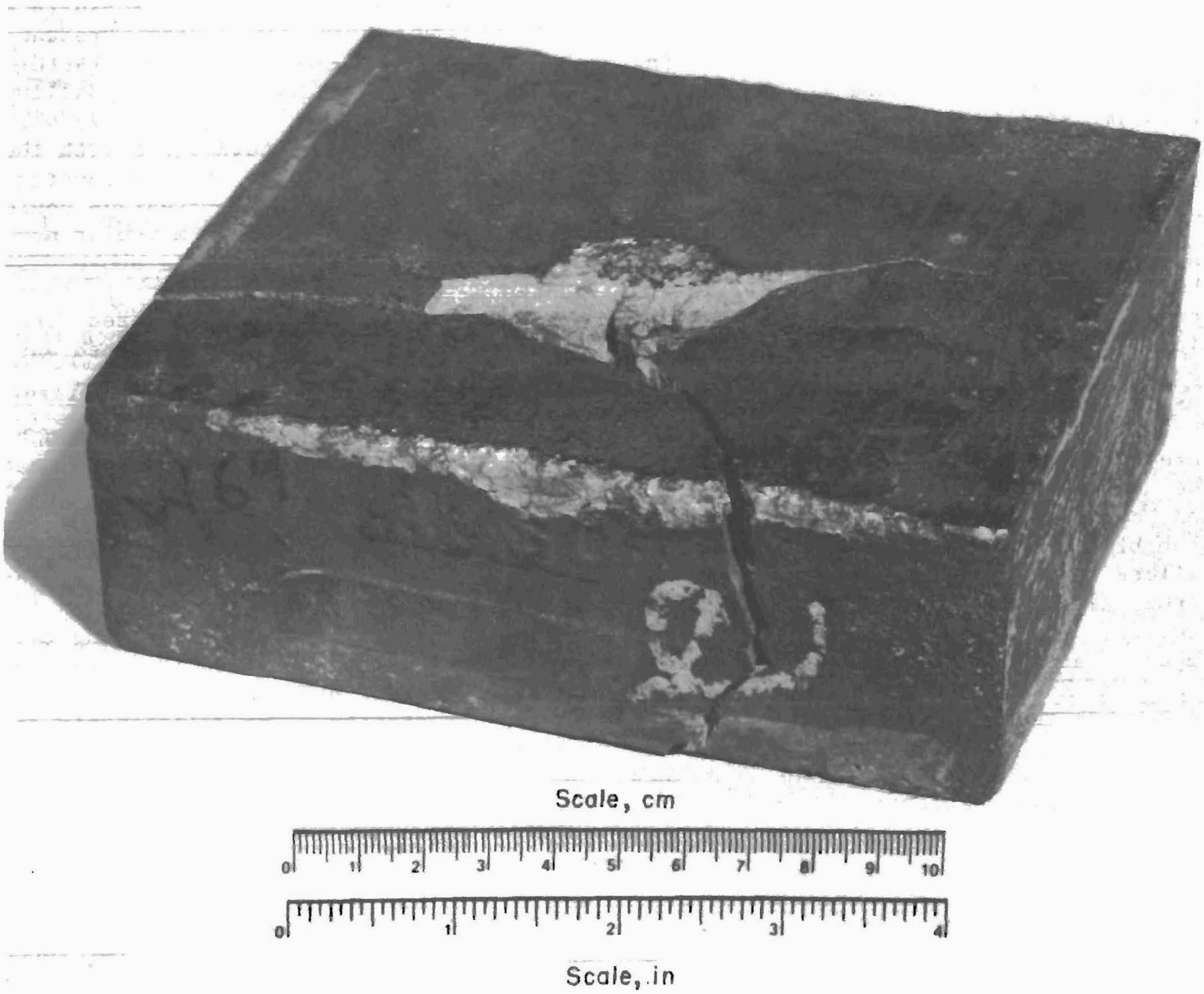

FIGURE 10. - Breakage of a test block. High Cr-Mo white cast iron (block 12c) after 40,300 impacts.

survived only 130 impacts. The block contained type A graphite, which is known to cause extreme brittleness.

HARDNESS AND MICROSTRUCTURE

Some general relations between hardness and the type of failure can be found from the data of table 3. Brinell hardness numbers (HB) were determined from indentations made with the 3,000-kg load. The softer test blocks (up to HB 555) generally failed by cold flow and flaking as a result of plastic deformation and extreme mechanical work hardening of the surface layers. Blocks with a hardness of HB 555 and greater, failed by spalling or breakage or both. It should be remembered that the abrasive wear resistance of most of these alloys will increase with increasing hardness. Therefore, some combination of hardness, spalling resistance, and breakage resistance must be optimized for a given application.

It can be assumed that microstructure and residual stresses determine whether the failure mode of hard materials is caused by spalling or breakage. From the microstructures described in table 2, several effects of microstructure on spalling and breakage can be observed. The graphite flakes in the microstructure of block 8 explain its early demise. The coarse prior dendritic structure and coarse martensite in blocks 6 and 9 probably contributed to their premature failure by breakage. The pearlitic structure of the cast iron in block 7, however, gave it a longer life, 33,400 impacts, and the pearlitic structure in the Cr-Mo steel gave it enough toughness to survive the full test.

The Cr-Mo white cast irons contained interdendritic eutectic carbides and dendrites with various combinations of austinite, tempered martensite, and secondary carbide precipitates. Block 13, which resisted spalling very well but eventually broke at 77,600 impacts, contained dendrites that had transformed to martensite by heat treatment. Block 14, on the other hand, which spalled excessively and did not break, contained austenitic dendrites with secondary carbide precipitates. This agrees with findings of others (8-9); namely, that austenite increases the fatigue life of the bulk casting but also increases the tendency to spall. Because spalling is also a fatigue process, the preceding statement seems somewhat contradictory. We suspect that retained austenite promotes spalling by reducing the short range, subsurface fatigue life while increasing breakage resistance by improving the fracture toughness of the casting. The spalling rates of blocks 12a, 12b, and 12c were intermediate, which would agree with the intermediate amount of observed austenite; the shorter life to breakage could be attributed to the more acicular morphology of the carbides. The above discussion is based on microstructural observations. It must be realized that accurate determination of retained austenite requires X-ray analysis (14).

In a detailed study of fracture toughness of white cast irons of various heat treatments and compositions, Sare (20) found few correlations except that retained austenite improved the fracture toughness. Diesburg (8) found a slight decrease in fracture toughness and an increase in hardness as the tempering temperature of a Cr-Mo white iron was increased, thereby presumably reducing the retained austenite. The relationship between retained austenite and spalling is being studied through additional research on white cast irons.

SUMMARY

A test machine was devised that can produce cold flow, spalling, or breakage of a test block in a relatively short time. These three modes of degradation are the same as found in real mill liners. A fourth mode, flaking, was identified in the test but is not found in real mills because the abrasive wear dominates.

The machine produces severe repeated impacts, at a rate of about 2,000 per hour, concentrated on a small region of a test block.

Cold flow occurred on the three softest alloys, mild steel, austenitic manganese steel, and high-carbon chromium steel (HB 156 to 415), and on the lean-manganese steel (HB 555) Flaking occurred on these four alloys and on two additional alloys, pearlitic Cr-Mo steel and pearlitic cast iron. Spalling or breakage or both occurred on the remaining test blocks, all with a hardness of HB 555 or greater. Spalling was observed only on the alloyed white cast irons.

The average weight loss rate was least for the soft alloys that flaked, ranging from 0.09 to 1.4 mg per impact. But these alloys suffered excessive cold flow and could be expected to have poor abrasion resistance (except for austenitic manganese steel). The weight loss rate was highest for the alloys that spalled, ranging from 1.6 to 5.1 mg per impact.

The test results agree with the established general relationships for mill liners--hard abrasion-resistant alloys tend to spall or break, and soft work-hardenable alloys tend to plastically deform. The results also confirm that high-chromium white cast irons have a tendency to spall but may not spall excessively if heat treated properly. The test may be useful for further investigations into the basic causes of spalling and breakage and establishing their relationship to the heat treatment, composition, and wear resistance of mill liner materials.

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